# Control of Inverters

## PulseWidth Modulation and Space Vector PWM

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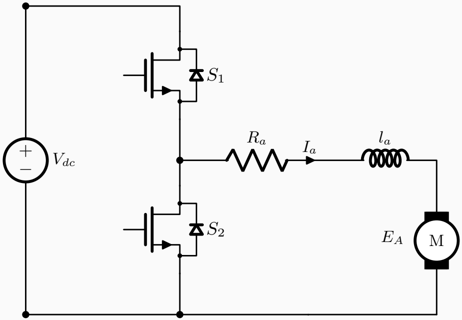
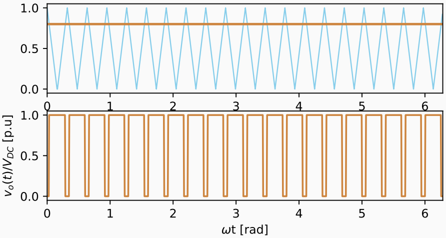
# DC to DC conversion and PWM

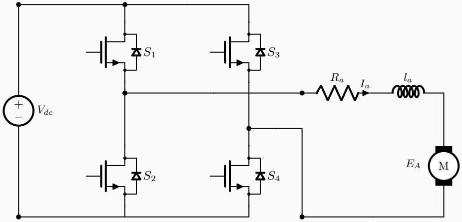
# Step-down Power converter




Sketch the armature current waveform.

# Step-down Power converter for 4 Quadrant



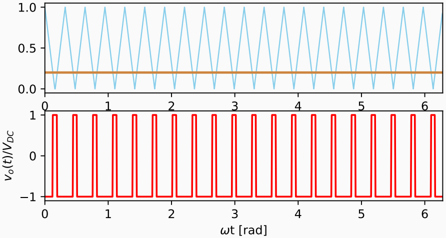

The average value of $v_a$ is

$$\bar{v}_a = \frac{1}{T_s} \int_0^{T_s} v_a(t)dt$$

$$\bar{v}_a = \frac{V_{dc} T_{on}}{T_s} - \frac{V_{dc}(T_s - T_{on})}{T_s}$$

$$\bar{v}_a = V_{dc}[2D - 1]$$

$$\text{where} D = \frac{T_{on}}{T_s}$$



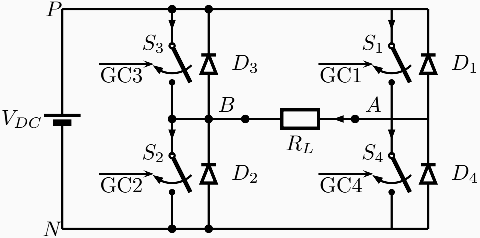

The output voltage $v_a$ is a pulsewidth modulated waveform. It has a period of $T_s$ and

$$v_a = V_{dc} \qquad 0 < t < T_{on}$$

$$v_a = -V_{dc} \qquad T_{on} < t < T_s$$

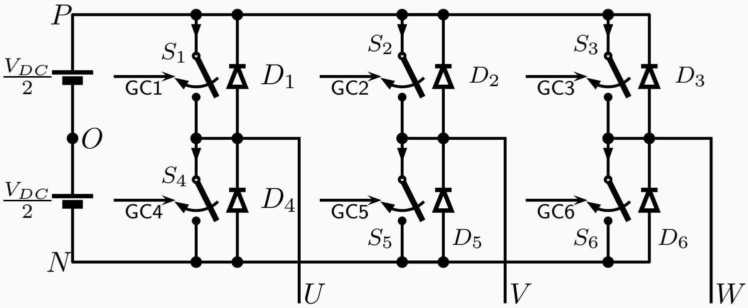
# DC to AC converter

# Producing AC from a DC source



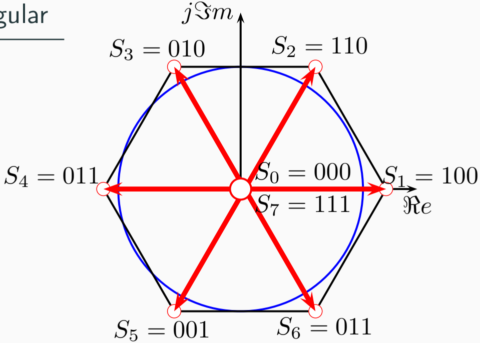

- Sketch the voltage waveform $v_{AB}$ for few complete AC cycles
- Sketch the current waveform $i_{AB}$ for the corresponding voltage cycles?
- Sketch the waveform for $GC1$ and $GC3$ for corresponding voltage cycles?

# 3 Phase Inverter Circuit



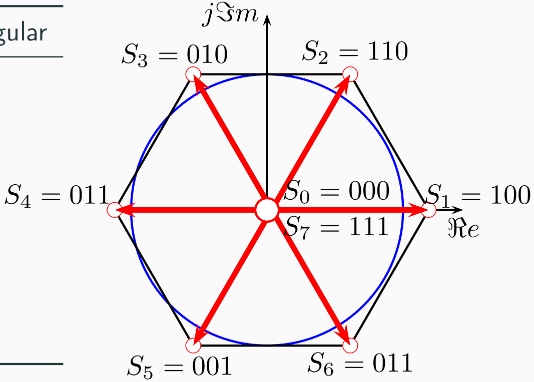
# Space Vectors associated with the switching states

| S | $v_s(S)$ Polar | $v_s(S)$ rectangular |
|---|---|---|
| 100 | $\frac{2}{3}V_{DC}e^{j0}$ | – |
| 110 | $\frac{2}{3}V_{dc}e^{j\frac{\pi}{3}}$ | – |
| 010 | $\frac{2}{3}V_{dc}e^{j\frac{2\pi}{3}}$ | – |
| 011 | $\frac{2}{3}V_{dc}e^{j\pi}$ | – |
| 001 | $\frac{2}{3}V_{dc}e^{j\frac{4\pi}{3}}$ | – |
| 101 | $\frac{2}{3}V_{dc}e^{j\frac{5\pi}{3}}$ | – |
| 111 | 0 | 0 + j0 |
| 000 | 0 | 0 + j0 |

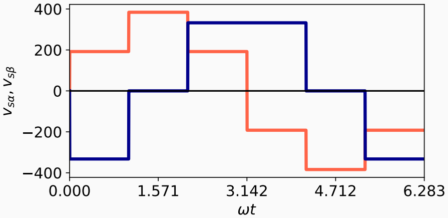


# Space Vectors during Six-Step Operation

| S | $v_s(S)$ Polar | $v_s(S)$ rectangular |
|---|---|---|
| 100 | $\frac{2}{3}V_{DC}e^{j0}$ | – |
| 110 | $\frac{2}{3}V_{dc}e^{j\frac{\pi}{3}}$ | – |
| 010 | $\frac{2}{3}V_{dc}e^{j\frac{2\pi}{3}}$ | – |
| 011 | $\frac{2}{3}V_{dc}e^{j\pi}$ | – |
| 001 | $\frac{2}{3}V_{dc}e^{j\frac{4\pi}{3}}$ | – |
| 101 | $\frac{2}{3}V_{dc}e^{j\frac{5\pi}{3}}$ | – |
| 111 | 0 | 0 + j0 |
| 000 | 0 | 0 + j0 |



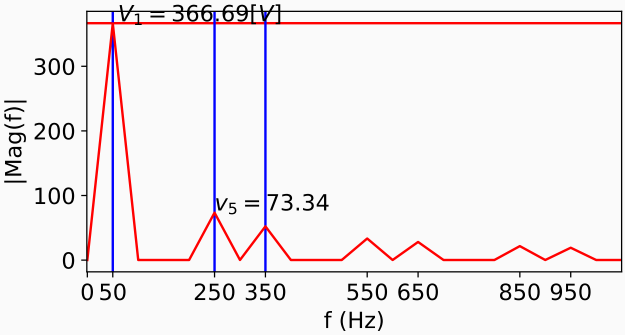
# Six-Step Operation




Switching each state for 1/6 of fundamental period produces a six-step operation

| switching state | $(S_U, S_V, S_W)$ |
|---|---|
| $S_1$ | 1 0 0 |
| $S_2$ | 1 1 0 |
| $S_3$ | 0 1 0 |
| $S_4$ | 0 1 1 |
| $S_5$ | 0 0 1 |
| $S_6$ | 1 0 1 |

# Six-Step Operation: Low Frequency Harmonics present




By Fourier Analysis, peak value of fundamental component of Six-Step Wave is

$$\hat{V}_{\text{six-step}} = \frac{2}{\pi} V_{DC}$$

Since $V_{DC} = 576$ [V], we get

$$\hat{V}_{\text{six-step}} = 366.69[\text{V}]$$

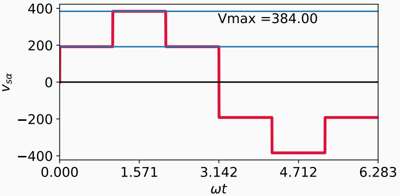
**Low freq,. harmonics**

- 5,7,11,13th harmonics are present
- Large filter needed to remove them

# Fourier Series of phase voltage

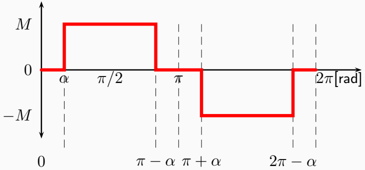
Fourier Series Quasi Square Wave

$$f(\omega t) = \sum_{h=1,3,5..}^{\infty} \frac{4M}{h\pi} cos(h\alpha) sin(h\omega t)$$




For square wave $\alpha = 0$, hence

$$f(\omega t) = \sum_{h=1,3,5..}^{\infty} \frac{4M}{h\pi} sin(h\omega t)$$

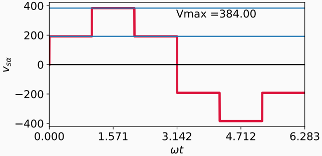



Phase voltage can be expressed of 2 waveforms

- A quasi square wave with $M = \frac{V_{DC}}{3}$ and $\alpha = \frac{\pi}{3}$
- and A Square wave with $M = \frac{V_{DC}}{3}$

Hence the fundamental component ($n = 1$) of the phase voltage during Six-step operation can be written as

# Fourier Series of phase voltage




Phase voltage can be expressed of 2 waveforms

- A quasi square wave with $M = \frac{V_{DC}}{3}$ and $\alpha = \frac{\pi}{3}$
- and A Square wave with $M = \frac{V_{DC}}{3}$

Hence the fundamental component ($n = 1$) of the phase voltage during Six-step operation can be written as

$$V_{1,\text{six-step}} = \frac{4}{\pi}\left(\frac{V_{DC}}{3}\right) cos\left(\frac{\pi}{3}\right) + \frac{4}{\pi}\left(\frac{V_{DC}}{3}\right) \tag{1}$$

$$V_{1,\text{six-step}} = \frac{4}{\pi}\left(\frac{V_{DC}}{3}\right)\left[1 + cos\left(\frac{\pi}{3}\right)\right] \tag{2}$$

$$V_{1,\text{six-step}} = \frac{4}{\pi}\left(\frac{V_{DC}}{3}\right)\left[1 + \frac{1}{2}\right] \tag{3}$$

$$V_{1,\text{six-step}} = \frac{2}{\pi} V_{DC} \tag{4}$$

# The maximum Fundamental Frequency voltage an Inverter can produce

## Maximum Fundamental Frequency voltage

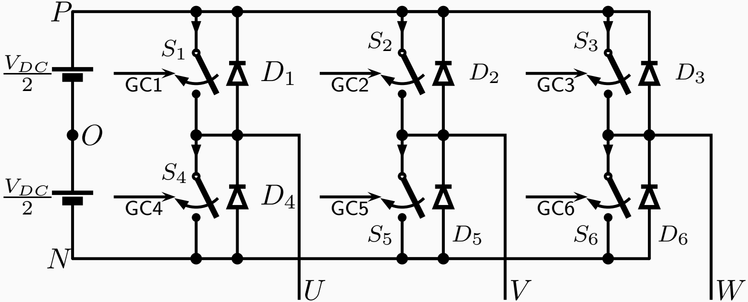
- During Six-step operation maximum voltage is produced by inverter
- The fundamental frequency voltage for six-step operation is found using fourier series
- Fundamental frequency can be changed by changing the fundamental period ($f_1 = 50$Hz is rated in Singapore)

The peak value of fundamental component of phase voltage during six-step is

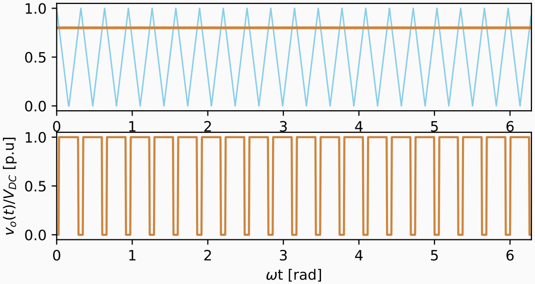
$$\hat{V}_{1,\text{six-step}} = \frac{2}{\pi} V_{DC} \tag{5}$$

# Sine Wave Pulse Width Modulation (SWPWM)

# 3 Phase Inverter Circuit

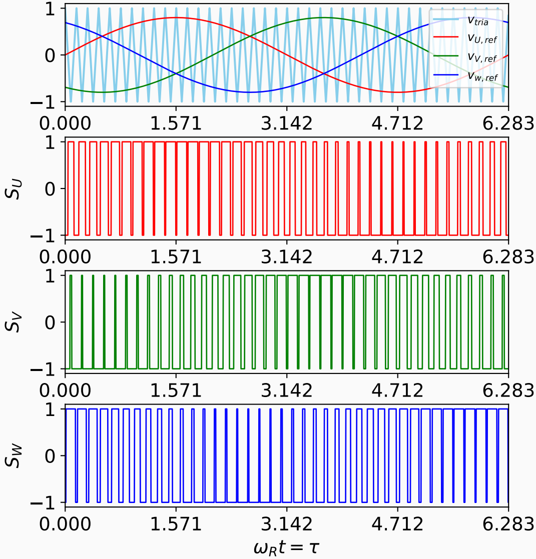


# Principle of Puslewidth Modulation (PWM)



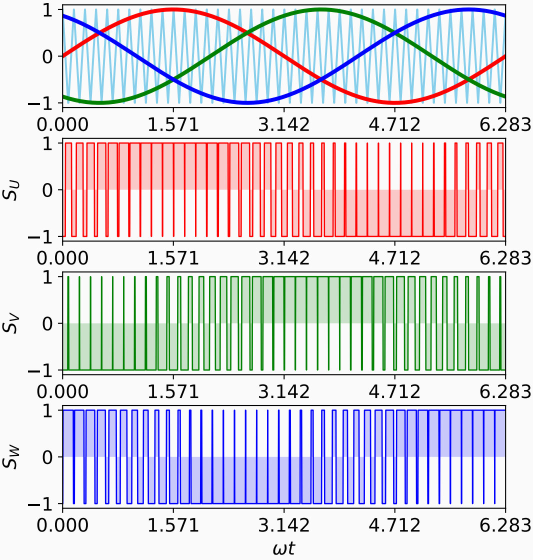

- Use a high frequency triangular carrier wave
- Compare it with desired reference wave
- When **if**$(V_{ref} > V_{carrier})$**then:**$S = 1.0$, **else:**$S = 0$
- Output is a high frequency switched waveform - peak value - constant
- Puslewidth of the waveform varies as the value of $V_{ref}(t)$

# 3 phase Sinewave Puslewidth Modulation (SWPWM)



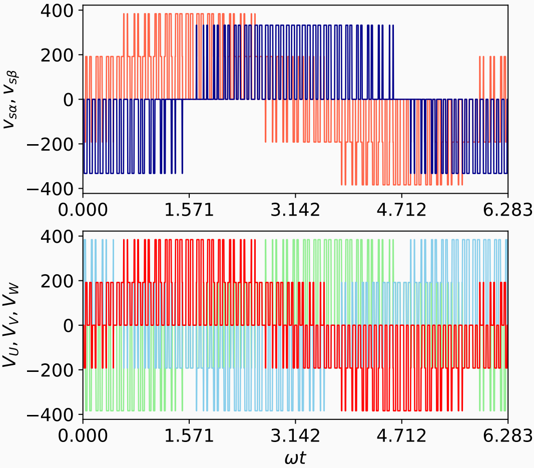

- Use a high frequency triangular carrier wave
- Compare it with 3 phase sinewave
- When **if**$(V_{ref} > V_{carrier})$**then:**$S = 1.0$, **else:**$S = 0$
- Logic Output used for switching $S = 1$**then**Top Switch on
- $S = 0$**then**bottom Switch on
- Inverter produces 3 phase voltages

# 3 phase Sinewave Puslewidth Modulation Averages per cycle (SWPWM)



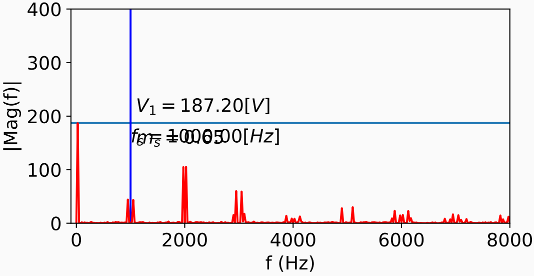

- Use a high frequency triangular carrier wave
- Compare it with 3 phase sinewave
- When **if**$(V_{ref} > V_{carrier})$**then:**$S = 1.0,$ **else:**$S = 0$
- Logic Output used for switching $S = 1$**then**Top Switch on
- $S = 0$**then**bottom Switch on
- Inverter produces 3 phase voltages

# 3 phase Sinewave Puslewidth Modulation (SWPWM)




- Top Graph - Space Vector Voltages
- Bottom Graph - 3 phase Voltages

# Why use PWM?




$$
\begin{aligned}
m_s &= \frac{\text{Peak value of reference}}{\text{Peak value of carrier}} \\
&= \frac{\hat{V}_{ref}}{\hat{V}_{carrier}}
\end{aligned}
$$

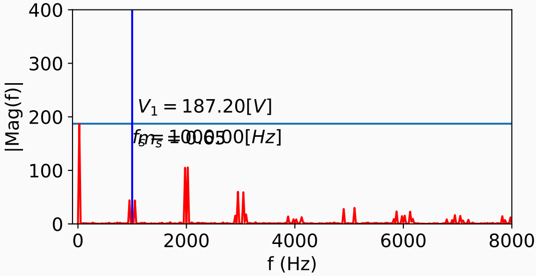
- The fundamental and harmonics get separated in frequency domain
- By using higher carrier frequency, dominant harmonics get pushed to right
- It becomes easier to filter higher harmonics with smaller filter size
- filter cut-off is $\omega_c = \frac{1}{\sqrt{LC}}$

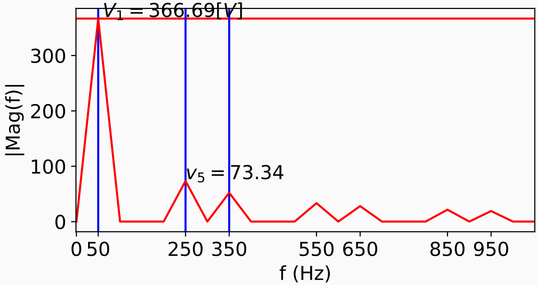
# General Definition of Modulation Index

For any type of PWM, Modulation index $m_i$ is defined as

$$m_i = \frac{\text{peak value of fundamental voltage produced by the PWM}}{\text{peak value of fundamental voltage during six-step}} = \frac{\hat{V}_{PWM}}{\frac{2}{\pi} V_{DC}} \tag{6}$$

# SWPWM does not allow us to get the maximum voltage




- for $V_{DC} = 576[\mathrm{V}]$
- max Voltage with SWPWM $= V_{DC}/2 = 288[\mathrm{V}]$
- max possible fundamental Voltage with Six Step $\frac{2}{\pi} V_{DC} = 366.69[\mathrm{V}]$

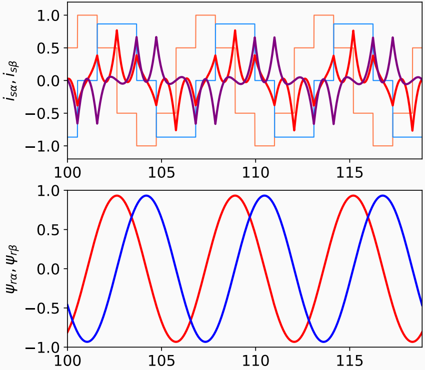
maximum modulation index in SWPWM

$$\hat{m}_{i,\mathrm{SWPWM}} = \frac{\frac{V_{DC}}{2}}{\frac{2}{\pi} V_{DC}} \tag{7}$$

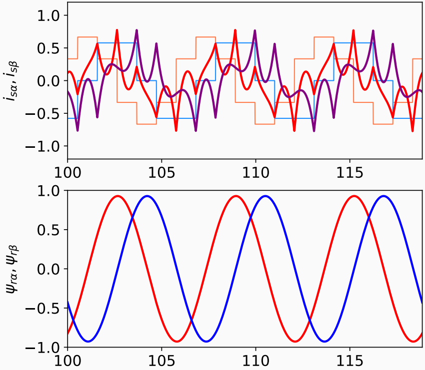
$$= \frac{\pi}{4} \tag{8}$$

$$= 0.785 \tag{9}$$

at no load




with loading



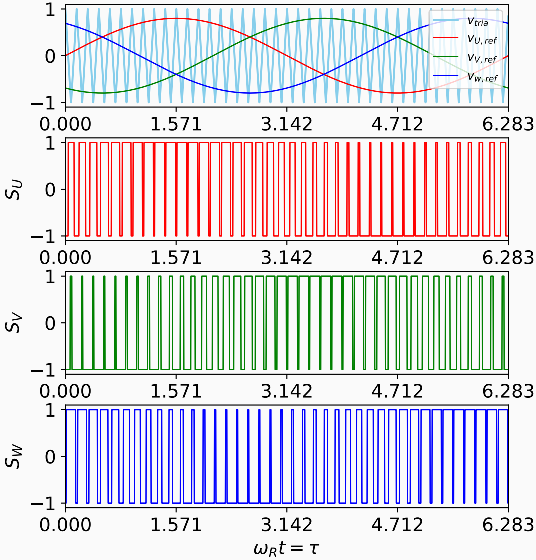

The current are non-sinusoidal with lower order harmonics. However, the flux is sinusoidal. This is because the impedance of the motor acts as low pass filter

# SWPWM cannot utilize the full voltage capability of the Inverter

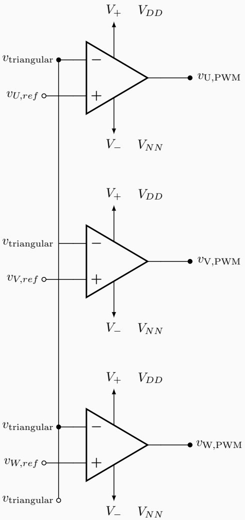
## SWPWM cannot produce the maximum voltage

- Maximum Fundamental voltage the SWPWM can produce is only $\frac{V_{DC}}{2}$
- Maximum Capability of 3 phase inverter is $\hat{V}_{1,\text{six-step}} = \frac{2}{\pi} V_{DC}$
- Hence SWPWM utilizes only 78% of the total voltage capability of the 3 phase inverter

# 3 phase Sinewave Puslewidth Modulation (SWPWM)




## Functional Circuit for PWM



# 3 phase Sinewave Puslewidth Modulation (SWPWM) Results

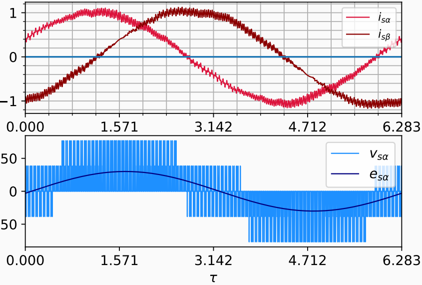



**Figure 1:** Motor currents space vector component (top) and $\alpha$ Stator voltage and back-emf (bottom)

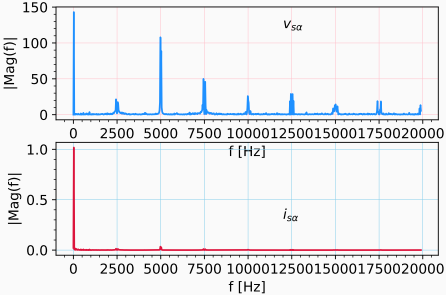



**Figure 2:** Sprectrums of voltage (top) and current (bottom)

## Motor impedance acts as filter

Though the applied stator voltage has high distortion due to PWM, the motor current harmonics are negligible as the motor impedance acts as low pass filter

# Comparison of stator currents SWPWM vs Six-Step

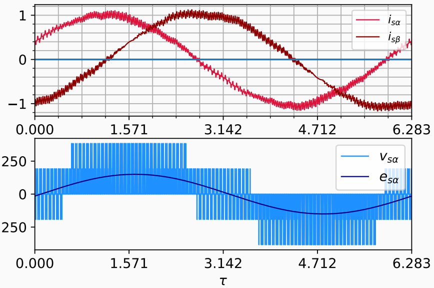



**Figure 3:** Motor currents space vector component (top) and $\alpha$ Stator voltage and back-emf (bottom)

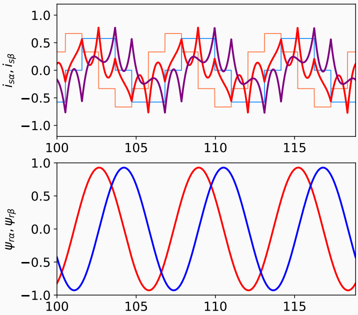



**Figure 4:** motor current due to Six-step operation

## PWM controlled inverter better

Current Distortion and Torque ripple in lower in PWM fed motors

# Increasing switching frequency lowers distortion

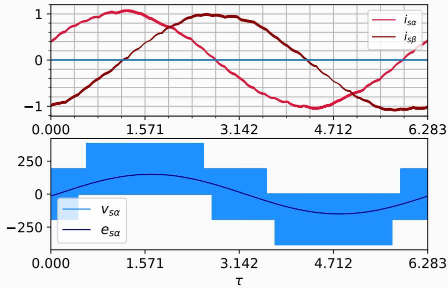



**Figure 5:** Motor currents space vector component (top) and $\alpha$ Stator voltage and back-emf (bottom)

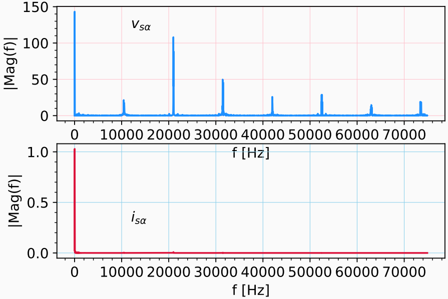



**Figure 6:** Sprectrums of voltage (top) and current (bottom)

## Motor impedance acts as filter

Higher the switching frequency, lower the distortion, so many researchers want to increase the switching frequency....but

# Increasing switching frequency causes higher iron losses

Usually Ferromagentic Iron used in core. Manufacture give loss density [W/kg] as

$$w_{Fe} = \underbrace{k_h f B^{\alpha}}_{\text{Hysteresis Loss}} + \underbrace{k_e f^2 B^2}_{\text{Eddy current Loss}} + \underbrace{k_a f^{3/2} B^{3/2}}_{\text{anomalous Loss}}$$

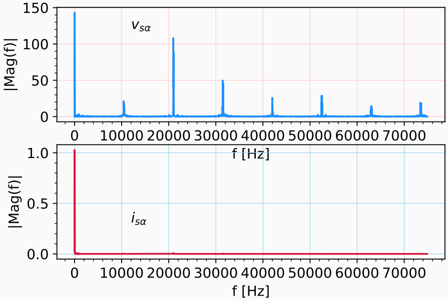


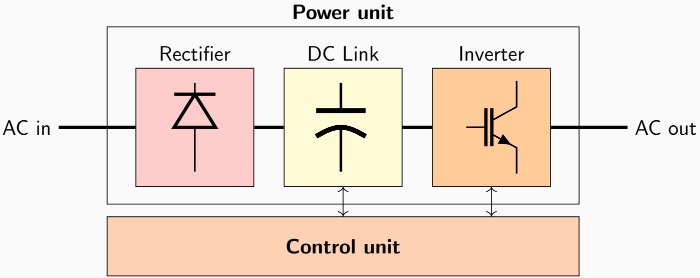

**Figure 7:** Sprectrums of voltage (top) and current (bottom)

### Motor impedance acts as filter

Higher the switching frequency, causes higher losses in iron of th e motor....The Irons losses are proportional to square of frequency

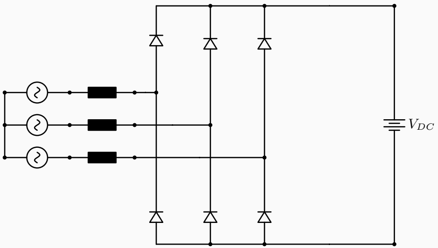
# Power Electronic System used in Drives

# Typical Single Quadrant AC drives

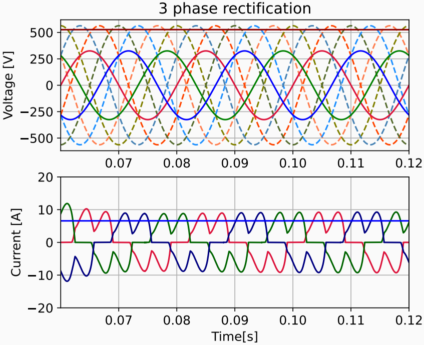



- AC input is converted into DC using 3 phase diode rectifier
- DC Link capacitor acts as energy storage
- DC Voltage is converter to 3 phase PWM AC voltage by 3 phase inverter

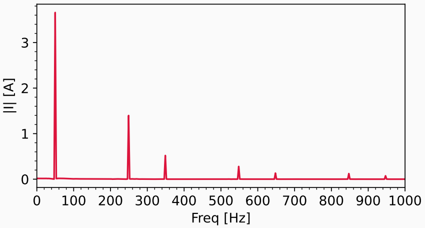
# Three phase Diode Rectifier: Distorted line current



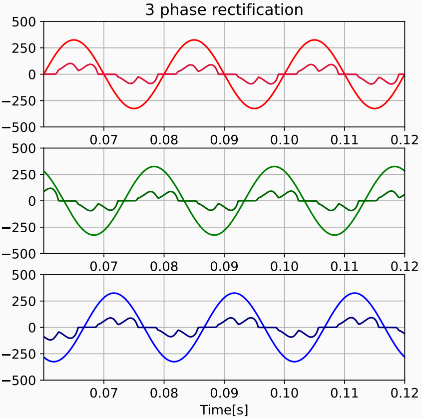

Diode in turns on when forward biased and turn-off when diode current goes to zero



# Three phase Diode Rectifier: Line current spectrum

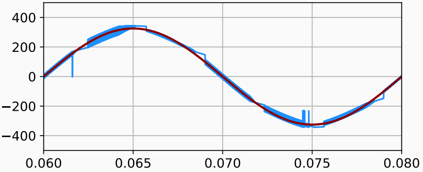



contains lower order odd harmonics 5,7,11,13...(3rd does not flow in a star connected 3 phase)



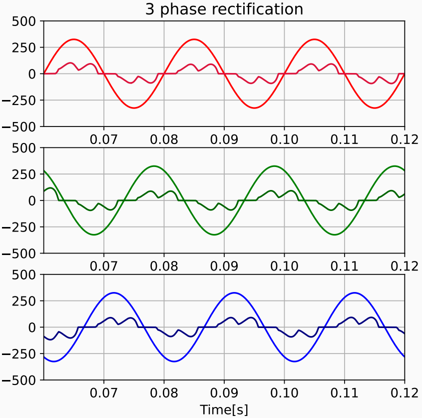

Individual phase currents

# Three phase Diode Rectifier: Distortion at PCC voltage due to distorted line currents



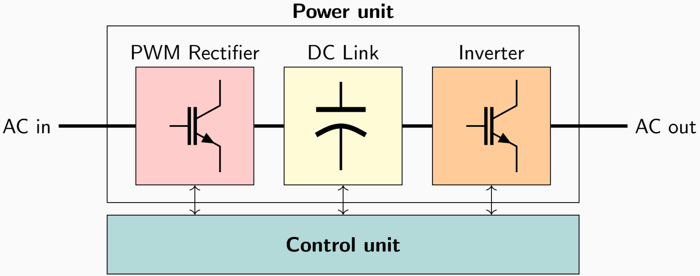

$$v_{pcc} = v_g - L_1 \frac{di_g}{dt}$$

Any other device connected at PCC sees distorted voltage, due to the non-sinusoidal voltage drop $L1\frac{dig}{dt}$ caused due to distorted currents




Individual phase currents

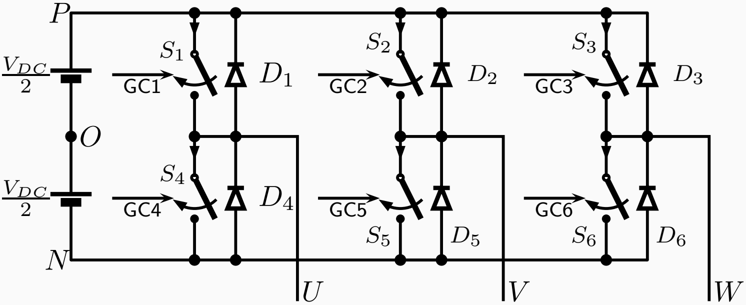
# 4 Quadrant AC drives




- AC input is converted into DC using 3 PWM rectifier, it gives unity power factor on the grid side
- DC Link capacitor acts as energy storage
- DC Voltage is converter to 3 phase PWM AC voltage by 3 phase inverter

# Space Vector Modulation (for knowledge only)

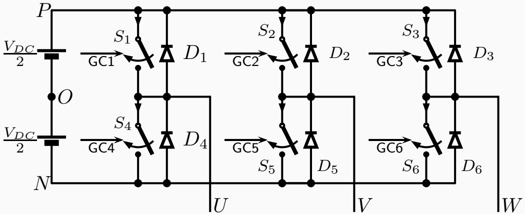
# 3 phase Voltage Source Inverter Circuit



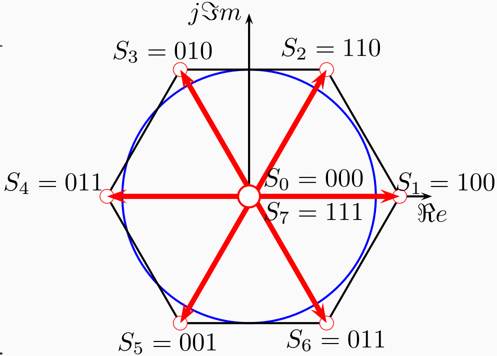

$$\vec{v}_s(S) = \frac{2}{3}\left(V_{U,N} + e^{j\frac{2\pi}{3}} V_{V,N} + e^{j\frac{4\pi}{3}} V_{W,N}\right) \tag{10}$$

$$\vec{v}_s(S) = \frac{2}{3} V_{DC}\left(S_U + e^{j\frac{2\pi}{3}} S_V + e^{j\frac{4\pi}{3}} S_W\right) \tag{11}$$

# Space Vectors and Switching state of 3p VSI

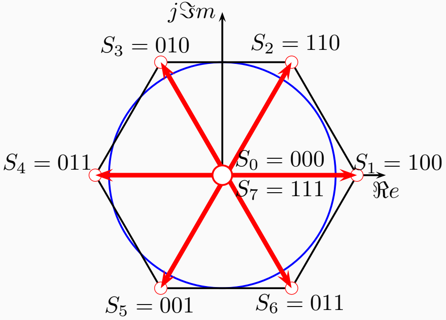



| switching state | $(S_U, S_V, S_W)$ |
|---|---|
| $S_0$ | 0 0 0 |
| $S_1$ | 1 0 0 |
| $S_2$ | 1 1 0 |
| $S_3$ | 0 1 0 |
| $S_4$ | 0 1 1 |
| $S_5$ | 0 0 1 |
| $S_6$ | 1 0 1 |
| $S_7$ | 1 1 1 |



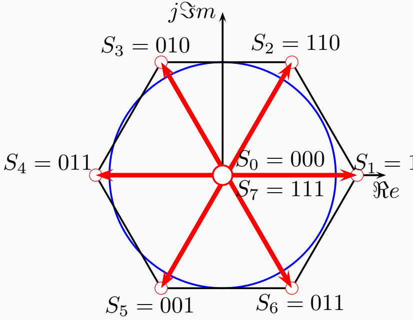
# Sectors of Space Vector Switching Plane

| Sector | angle |
|---|---|
| Sec(0) | $0 \rightarrow \frac{\pi}{3}$ |
| Sec(1) | $\frac{\pi}{3} \rightarrow \frac{2\pi}{3}$ |
| Sec(2) | $\frac{2\pi}{3} \rightarrow \pi$ |
| Sec(3) | $\pi \rightarrow \frac{4\pi}{3}$ |
| Sec(4) | $\frac{4\pi}{3} \rightarrow \frac{5\pi}{3}$ |
| Sec(5) | $\frac{5\pi}{3} \rightarrow 2\pi$ |



# Space Vectors associated with the switching states

| S | $v_s(S)$ Polar | $v_s(S)$ rectangular |
|---|---|---|
| 100 | $\frac{2}{3}V_{DC}e^{j0}$ | – |
| 110 | $\frac{2}{3}V_{dc}e^{j\frac{\pi}{3}}$ | – |
| 010 | $\frac{2}{3}V_{dc}e^{j\frac{2\pi}{3}}$ | – |
| 011 | $\frac{2}{3}V_{dc}e^{j\pi}$ | – |
| 001 | $\frac{2}{3}V_{dc}e^{j\frac{4\pi}{3}}$ | – |
| 101 | $\frac{2}{3}V_{dc}e^{j\frac{5\pi}{3}}$ | – |
| 111 | 0 | 0 + j0 |
| 000 | 0 | 0 + j0 |



# Definition of Space vector Modulation

**Definition**

The volt-second produced by the reference voltage space vector $\vec{v}_s^*$ in period $T_s$ should be equal to the voltage-seconds produced by the switching state vectors.

In a given sector, with vertices $\vec{v}_r$, $\vec{v}_l$ and zero vectors $v_0, v_7$, we can write the volt-sec balance as

$$\vec{v}_s^* T_s = \vec{v}_r t_a + \vec{v}_l t_b + v_0 t_0 \tag{12}$$

and

$$T_s = t_r + t_l + t_0$$

# Space Vector Modulation SVM or SVPWM

$$\vec{v}_s^* T_s = \vec{v}_r t_r + \vec{v}_l t_l + v_0 t_0 \quad (13)$$

$$\vec{v}_s^* T_s = \vec{v}_r t_r + \vec{v}_l t_l \quad (14)$$

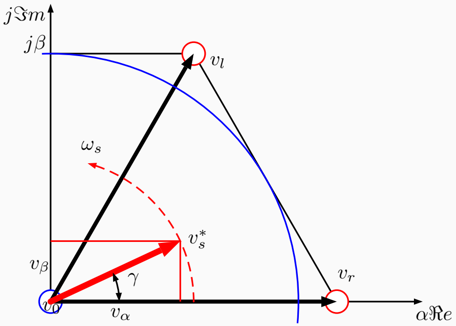
$$T_s = t_r + t_l + t_0 \quad (15)$$

$$v_{s\beta}^* = \vec{v}_l sin\left(\frac{\pi}{3}\right) t_l \quad (16)$$

$$\therefore t_l = \frac{v_{s\beta}^*}{|\vec{v}_l| sin\left(\frac{\pi}{3}\right)} T_s \quad (17)$$

$$\frac{t_l}{T_s} = \frac{v_{s\beta}^*}{\frac{2}{3} V_{DC} sin\left(\frac{\pi}{3}\right)} \quad (18)$$

$$\frac{t_l}{T_s} = \frac{|\vec{v}^*|}{\frac{2}{3} V_{DC}} \frac{sin(\gamma)}{sin\left(\frac{\pi}{3}\right)} \quad (19)$$



# SVM switching Times $t_r$

$$\vec{v}_s^* T_s = \vec{v}_r t_r + \vec{v}_l t_l + v_0 t_0 \qquad (20)$$

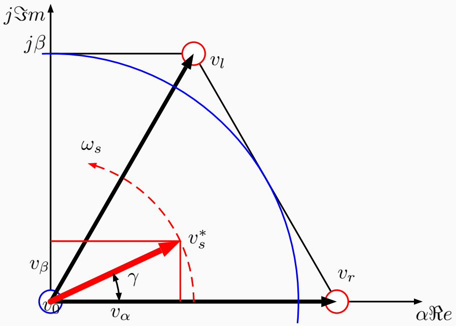
$$\vec{v}_s^* T_s = \vec{v}_r t_r + \vec{v}_l t_l \qquad (21)$$

$$T_s = t_r + t_l + t_0 \qquad (22)$$

$$v_{s\alpha}^* = \vec{v}_r t_r + \vec{v}_l cos\left(\frac{\pi}{3}\right) t_l \qquad (23)$$

substituting $t_l$ in above equation we get

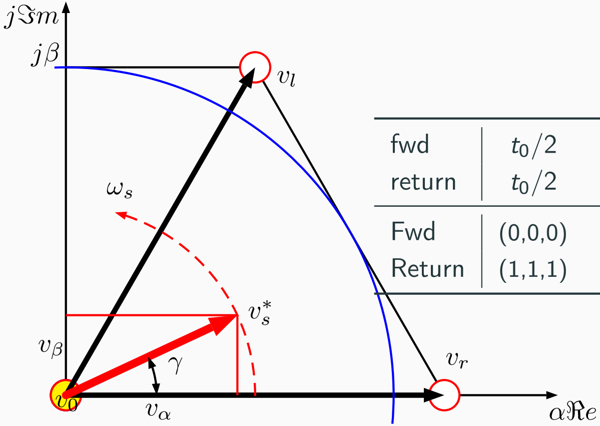
$$t_r = \frac{|\vec{v}^*|}{\frac{2}{3} V_{DC}} \frac{sin(\frac{\pi}{3} - \gamma)}{sin\left(\frac{\pi}{3}\right)} T_s \qquad (24)$$



# Switching Sequence of SVM in Sector 0

| on times | $t_0/2$ | $t_r$ | $t_l$ | $t_0/2$ | $t_0/2$ | $t_l$ | $t_r$ | $t_0/2$ |
|---|---|---|---|---|---|---|---|---|
| vector | $\vec{V}_0$ | $\vec{V}_r$ | $\vec{V}_l$ | $\vec{V}_7$ | $\vec{V}_7$ | $\vec{V}_l$ | $\vec{V}_r$ | $\vec{V}_0$ |
| Sec(0) | $S_0$ | $S_1$ | $S_2$ | $S_7$ | $S_7$ | $S_2$ | $S_1$ | $S_0$ |
| State | (0,0,0) | (1,0,0) | (1,1,0) | (1,1,1) | (1,1,1) | (1,1,0) | (1,0,0) | (0,0,0) |

# Switching Sequence in sector 0

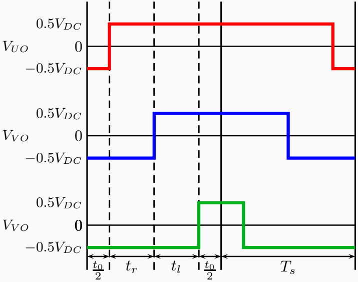



| | | | | |
|---|---|---|---|---|
| fwd | $t_0/2$ | $t_r$ | $t_l$ | $t_0/2$ |
| return | $t_0/2$ | $t_l$ | $t_r$ | $t_0/2$ |
| Fwd | (0,0,0) | (1,0,0) | (1,1,0) | (1,1,1) |
| Return | (1,1,1) | (1,1,0) | (1,0,0) | (0,0,0) |

# For the sequence in sector zero sketch $v_{s\alpha}, v_{s\beta}$

| | | | | |
|---|---|---|---|---|
| fwd | $t_0/2$ | $t_r$ | $t_l$ | $t_0/2$ |
| return | $t_0/2$ | $t_l$ | $t_r$ | $t_0/2$ |
| Fwd | (0,0,0) | (1,0,0) | (1,1,0) | (1,1,1) |
| Return | (1,1,1) | (1,1,0) | (1,0,0) | (0,0,0) |

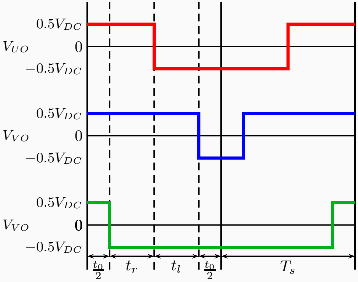
# Phase Voltages with respect to DC link Mid-point




sector 0 sequence

| | | | | |
|---|---|---|---|---|
| fwd | $t_0/2$ | $t_r$ | $t_l$ | $t_0/2$ |
| return | $t_0/2$ | $t_l$ | $t_r$ | $t_0/2$ |
| Fwd | (0,0,0) | (1,0,0) | (1,1,0) | (1,1,1) |
| Return | (1,1,1) | (1,1,0) | (1,0,0) | (0,0,0) |

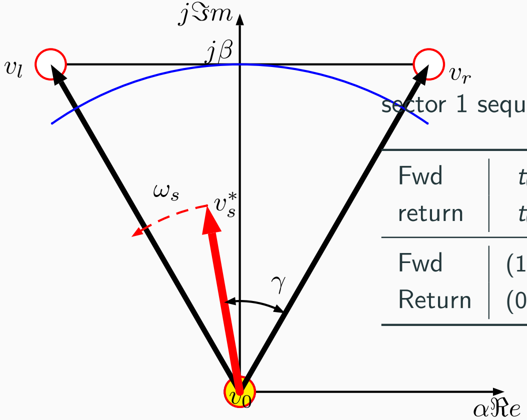
# Phase Voltages with respect to DC link Mid-point




sector 1 sequence

| | | | | |
|---|---|---|---|---|
| Fwd | $t_0/2$ | $t_r$ | $t_l$ | $t_0/2$ |
| return | $t_0/2$ | $t_r$ | $t_l$ | $t_0/2$ |
| Fwd | (1,1,1) | (1,1,0) | (0,1,0) | (0,0,0) |
| Return | (0,0,0) | (0,1,0) | (1,1,0) | (1,1,1) |

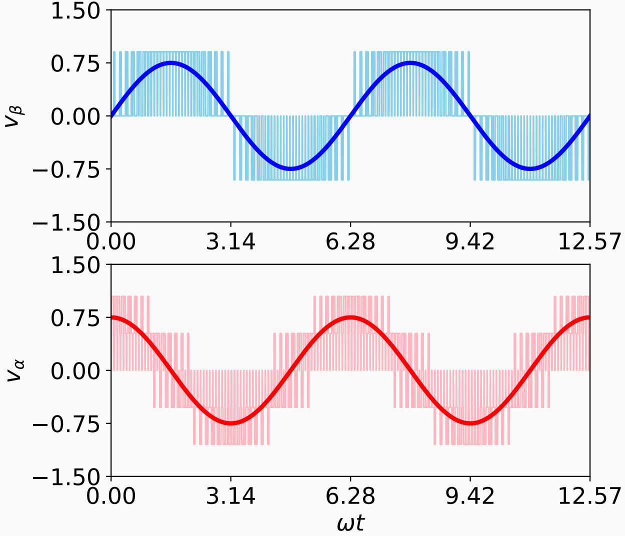
# Switching Sequence in sector 1




sector 1 sequence

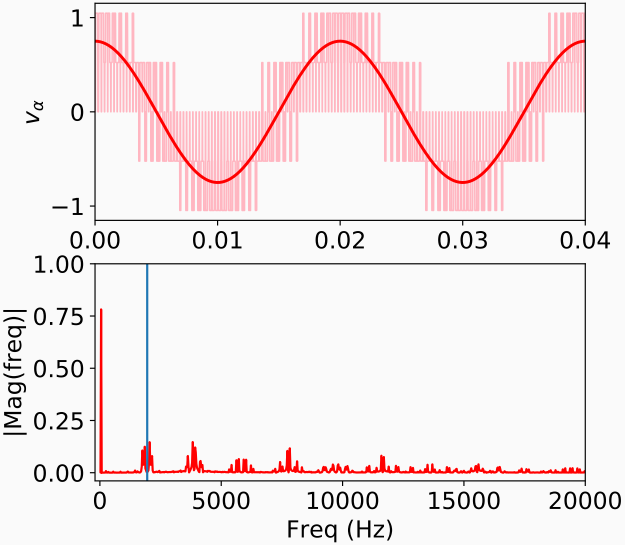
| | | | | |
|---|---|---|---|---|
| Fwd | $t_0/2$ | $t_r$ | $t_l$ | $t_0/2$ |
| return | $t_0/2$ | $t_r$ | $t_l$ | $t_0/2$ |
| Fwd | (1,1,1) | (1,1,0) | (0,1,0) | (0,0,0) |
| Return | (0,0,0) | (0,1,0) | (1,1,0) | (1,1,1) |

# Space Vector Modulation voltages




- Modulation index $m_i = 0.75$
- Switching frequency $f_s = 39 * 50\text{kHz}$
- Fundamental Frequency $f_1 = 50\text{Hz}$
- Normalization base $V_{1,\text{six-step}=\frac{2}{\pi}V_{DC}}$
- Normalized peak value of $v_{s\alpha} = \frac{\frac{2}{3}V_{DC}}{\frac{2}{\pi}V_{DC}} = \frac{\pi}{3}$

# Space Vector Modulation phase voltage and Spectra

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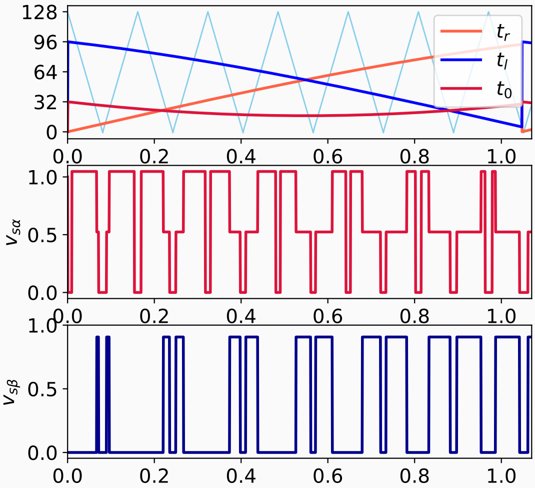
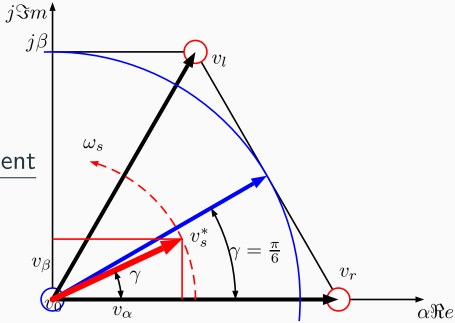
- Normalized peak value of $v_{s\alpha} = \frac{\frac{2}{3}V_{DC}}{\frac{2}{\pi}V_{DC}} = \frac{\pi}{3}$

# SVM switching times in Sector 0




- 128 bit counters is $2f_s$
- $t_r$, $t_l$ and $t_0$ change with angle/time
- $v_{s\alpha}$ has PWM output

# Maximum fundamental frequency Voltage produced by SVM




**SVM**

Maximum Fundamental Frequency component

Length of space vector $= \frac{2}{3} V_{DC}$
when blue circle touches hexagon,
magnitude of reference voltage will be

$$\hat{V}_{1,svm} = \frac{2}{3} V_{DC} cos\left(\frac{\pi}{6}\right) \tag{25}$$

$$\hat{V}_{1,svm} = \frac{2}{3} \frac{\sqrt{3}}{2} V_{DC} \tag{26}$$

$$\hat{V}_{1,SVM} = 0.577 V_{DC} \tag{27}$$

- Red dotter circle describes the trajectory of fundamental voltage
- Maximum fundamental voltage trajectory is given by blue circle
- At $\gamma = \frac{\pi}{6}$, $t_0 = 0$ when blue circle touches the hexagon

# Maximum Modulation Index for SVM

The maximum modulation index using SVM is

$$\hat{m}_{i,svm} = \frac{\text{maximum fundamental voltage by SVM}}{\text{maximum fundamental voltage during six-step}} \tag{28}$$

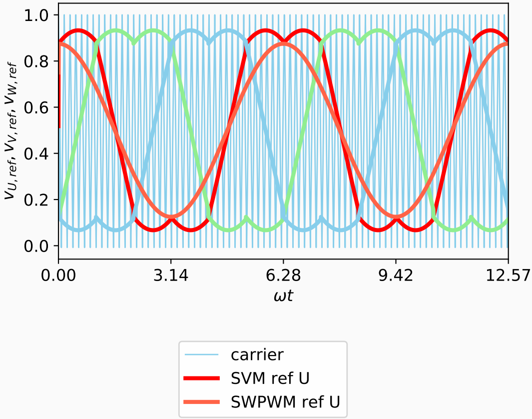
$$\hat{m}_{i,svm} = \frac{0.577 V_{DC}}{\frac{2}{\pi} V_{DC}} \tag{29}$$

$$\hat{m}_{i,svm} = 0.906 \tag{30}$$

**SVM utilizes voltage capacity better than SWPWM**

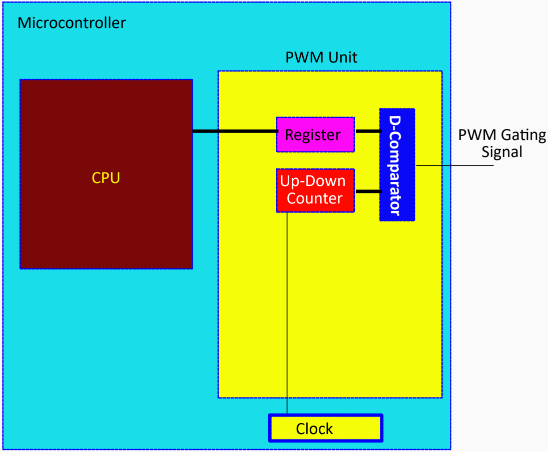
Hence SVM utilizes 90.6% of the installed voltage capability

# Why SVM produces more fundamental voltage than SWPWM



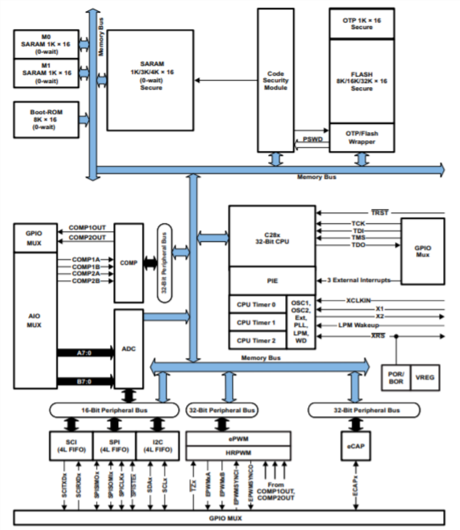

- The sinewave reference is used in SWPWM
- But, SVM produces a reference that has
- 3rd harmonic component add to fundamental
- Triplen ( x 3) harmonics do not flow in 3 phase circuits.

# Implementing PWM in Practice

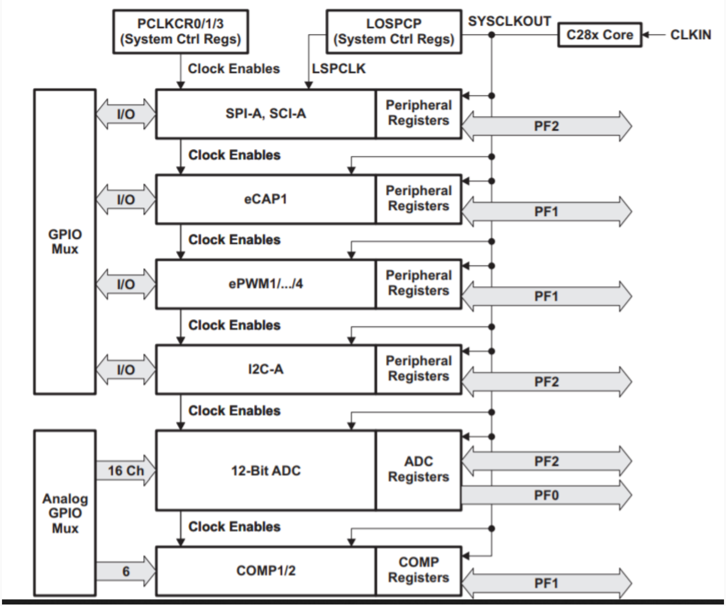



- Every Microcontroller has a count-n-compare unit
- Consists of an Up-down counter
- A set of registers (3 for 3 phase needed)
- A comparator
- A buffered output to drive the gate of Inverter

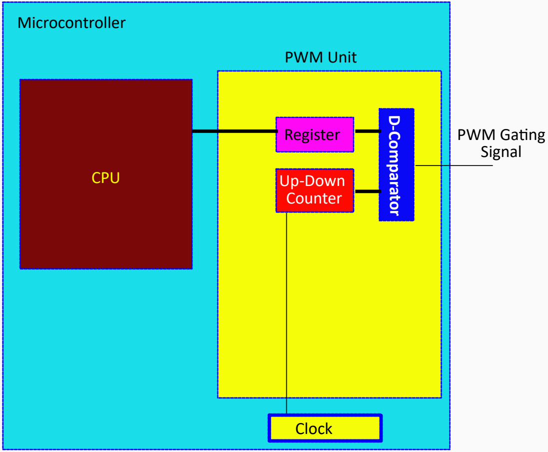
# Example of Practical Microcontroller FBD



# Example of Practical Microcontroller output unit

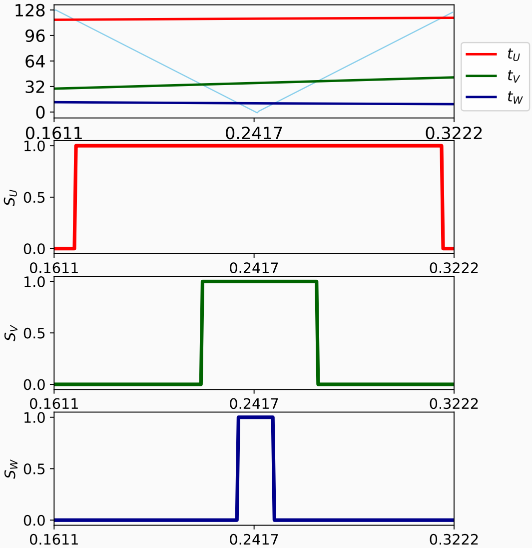


# Implementing PWM in Practice




- Compute $t_r$, $t_l$ and $t_0$
- Depending on position of reference voltage vector,
- compute $t_U$, $t_V$ and $t_W$
- Put the values in Registers
- Compare with counter
- D-Comparator output to gate drive unit

# Implementing PWM in Practice



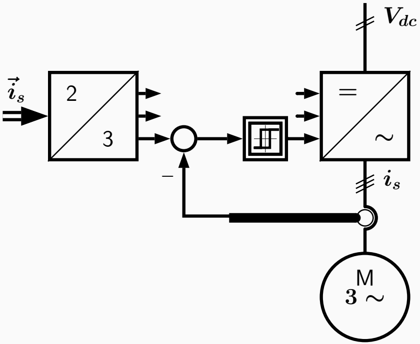

- Compute $t_r$, $t_l$ and $t_0$
- Depending on position of reference voltage vector,
- compute $t_U$, $t_V$ and $t_W$
- Put the values in Registers
- Compare with counter
- D-Comparator output to gate drive unit

# Current Control of Inverters

# Current Control of Inverters

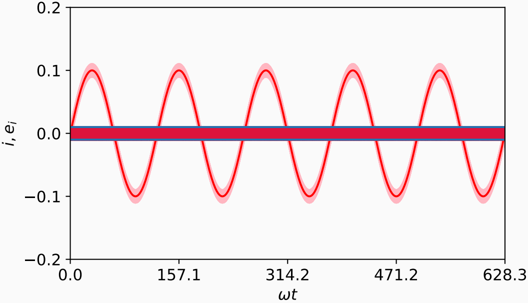
- For AC drives we need current control
- VSI is essentially a controlled voltage source
- 3 phase AC output can be generated using PWM methods (SWPWM, SVM)
- How do we get current control

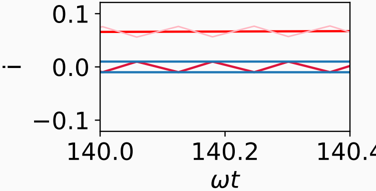
# Non-linear Current Control

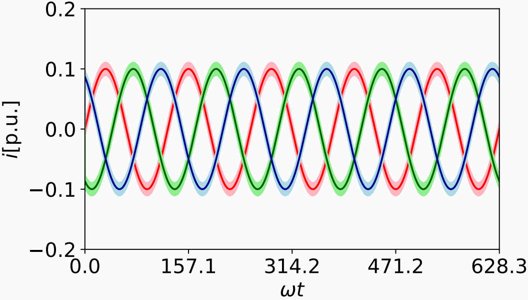



- Actual Current is compared with reference current
- A non-linear (Bang-Bang controller) is used to produce switching states
- Hysteresis is added in practices and that decides the switching frequency
- The Switching frequency is not constant
- Suited for low power application with fast dynamic
- Basic Idea: Analog control paradigm using Comparators

# Non-linear Current Control

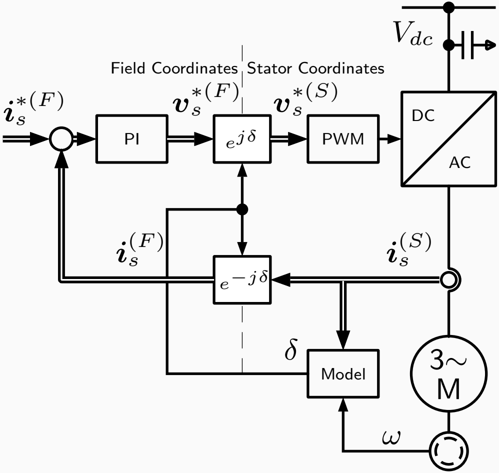


# Linear Current Control: PI Control in Field Coordinates

- In field coordinates, we see currents as DC (zero frequency)
- This is due to coordinate transform in a synchronous frequency reference frame
- It is called Field-oriented Current control as the reference frame is oriented along rotor flux space vector



# Non-linear Current Control vs Linear Current Control

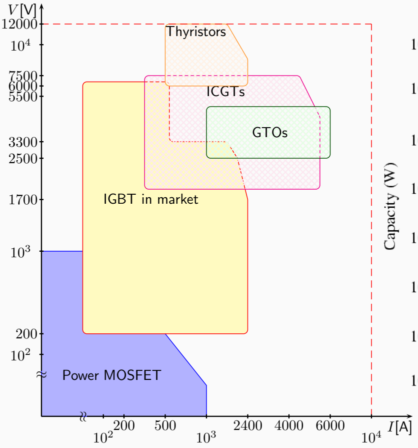
Non-linear Current Control

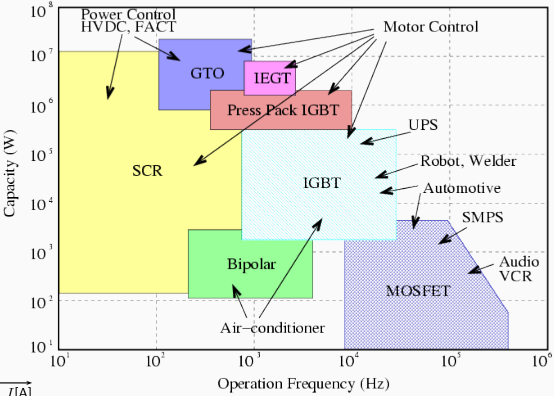
+ Fast Response
+ Parameter dependency is less
+ Good for analog implementation
- Switching frequency keeps varying
- Switching frequency depends on parameters
- Suited for low power applications
- Many implement Non-linear control digitally, so they loose the advantage of analog

Linear Current Control

+ Switching frequency can be decided
+ Control performance + PWM performance can be chosen
+ Digital Implementation is easier
- Parameter dependent performance (can be tuned)
- Transient Response depends on controller characteristics
- Digital Implementation: Transient response

# Power Electronic devices used in VSC for drives



# References i